

Sea surface temperature east of Australia: A predictor of tropical cyclone frequency over the western North Pacific?

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The relationship between sea surface temperature (SST) east of Australia and tropical cyclone frequency over the western North Pacific (WNPTCF) is analyzed by use of observation data. The WNPTCF from June to October is correlated negatively to spring SST east of Australia. When the spring SST is in the positive phase, a cyclonic circulation anomaly in the upper troposphere and an anticyclonic circulation anomaly in the lower troposphere prevail over the western North Pacific from June to October, concurrent with an anomalous atmospheric subsidence and an enlarged vertical zonal wind shear. These conditions are unfavorable for tropical cyclone genesis, and thus WNPTCF decreases. The negative phase of the spring SST east of Australia leads to more tropical cyclones over the western North Pacific. The spring SST east of Australia may give rise to simultaneous change in tropical atmospheric circulation via the teleconnection wave train, and then subsequently affect atmospheric circulation variation over the western North Pacific.

western North Pacific, tropical cyclone frequency, sea surface temperature, atmospheric circulation, teleconnection

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Tropical cyclones (TCs) are a strongly synoptic phenomenon generated over tropical oceans. Their occurrence often engenders rainstorms and storm surges, which in many countries results in economic loss and human deaths. Because TCs occur most frequently over the western North Pacific (WNP), the interannual variability in and predictability of TC activity in this region is of prime interest. Research on this issue can improve understanding the mechanisms of TC variation and provide a scientific basis for short-term prediction, thereby enhancing defense ability against such disastrous weather and reducing losses.

Many studies have been conducted to determine the genesis, evolution, and the relevant climate characteristic of TCs over the WNP [1–5]. Variations in TC activity are determined mainly by the large-scale atmospheric circulation system and the ocean temperature condition. The monsoon

trough, stratospheric quasi-biennial oscillation, Madden-Julian oscillation and Rossby-gravity wave all can exert significant impacts on TC activity over the WNP [2,6–10]. In recent years, several studies have further investigated the influence of atmospheric modes on tropical cyclone frequency over the western North Pacific (WNPTCF). Wang et al. [11,12] showed that WNP typhoon number during June to September is correlated negatively to the Antarctic oscillation and positively to the North Pacific oscillation. Zhou et al. [13] and Cui et al. [14] found that a strong (weak) Asian-Pacific oscillation in summer is advantageous (disadvantageous) for TC genesis, and thus TC frequency increases (decreases) over the WNP.

Many studies have highlighted that El Niño-Southern Oscillation (ENSO) can significantly affect TC frequency, intensity and location over the WNP by influencing ocean temperature, through changes in the magnitude of the vertical zonal wind shear, Walker circulation, monsoon trough

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etc. [15–21]. Additionally, thermal states in the warm pool also have effects on TC activity over the WNP. During the warm state there are fewer typhoons and tropical storms tend to form in the northwest of the WNP and move westward. During the cold state typhoons appear in the southeast WNP [22,23].

Because China suffers from TCs over the WNP, it is essential to carry out predictions of TC activity in this region. To perform better predictions, antecedent signals have been widely sought. For example, Zhou and Cui [24,25] examined the relationship between the spring Hadley circulation and summer WNPTCF. Their results showed that a strong (weak) phase of the spring Hadley circulation corresponded to lower (higher) WNPTCF. Chan et al. [26,27] analyzed WNPTCF variability in the years before, when and after El Niño or La Niña happened, and applied ENSO as an important seasonal indicator of TC activity over the WNP. Fan [28] proposed that large sea ice cover in the North Pacific during winter and spring tends to decrease WNPTCF, and used it as a new predictor to establish a forecast model [29,30].

Interannual variability in TC activity over the WNP is complicated, and identifying other crucial factors is important for characterizing TC variability and predictability. It has been noted that atmospheric circulations in the Southern Hemisphere are tightly connected to the typhoon activity [31–33]. If SST change directly affects atmospheric circulations, is Southern Hemispheric SST linked to TC activity over the WNP? If so, can it be employed as a potential indicator in predicting TCs over the WNP? Since previous studies focused mainly on the influence of Northern Hemispheric SST and paid less attention to the influence of Southern Hemispheric SST, the present study addresses the linkage between Southern Hemispheric SST and WNPTCF.

1 Data

The datasets used were (1) NCEP/NCAR reanalysis data [34] with horizontal resolution of $2.5^\circ \times 2.5^\circ$, (2) NOAA SST data [35] with horizontal resolution of $2^\circ \times 2^\circ$, and (3) TC record provided by the Joint Typhoon Warning Center (JTWC) [36]. Generally, TCs are classified into tropical depressions, tropical storms and typhoons, depending on their maximum sustained wind speeds. In this study, TCs refer only to tropical storms and typhoons. Time series for the analysis covers the period 1971–2005.

2 Results

Figure 1 shows correlations between the June–October (JJASO) mean WNPTCF and the spring (MAM) and JJASO SST. There were significant negative correlations in the region east of Australia, with the maximum value above

–0.5 (Figure 1(a)). Such an out-of-phase relationship also existed in JJASO (Figure 1(b)), but the significance area was smaller than that in Figure 1(a). This suggests that the SST east of Australia in spring has larger effects than its counterpart in JJASO on the JJASO WNPTCF. To assess the possible influence of the linear trend, we further calculated correlations between JJASO WNPTCF and the spring and JJASO SST after filtering. Interestingly, the correlation pattern after detrending (Figure not shown) conforms to that presented in Figure 1. Other research [15–21] has shown that ENSO is linked closely to TC activity over the WNP. To identify the possible influence of ENSO, we also computed SST–WNPTCF correlations after removing the ENSO signal. The correlation pattern resembles that before removing ENSO signal.

To describe temporal variation in the SST east of Australia, we defined an index (EASST) as the regional mean SST within the significance area shown in Figure 1(a). The time series of the spring EASST and JJASO WNPTCF is shown in Figure 2(a). The out-of-phase relationship between them is very prominent, with correlation coefficients of –0.57 and –0.55, respectively, for the non-detrended and detrended results, both significant at the 99.9% level. The negative correlation is remarkable after the late 1980s compared with earlier, reflecting an interdecadal change. This phenomenon may be related to the interdecadal climate transition occurring in the late 1980s [37–39]. The ENSO event also exhibits interdecadal change during the 20th century [40]. However, detailed mechanisms need to be studied further. Figure 2(b) shows correlations between JJASO WNPTCF and the EASST in each month. The

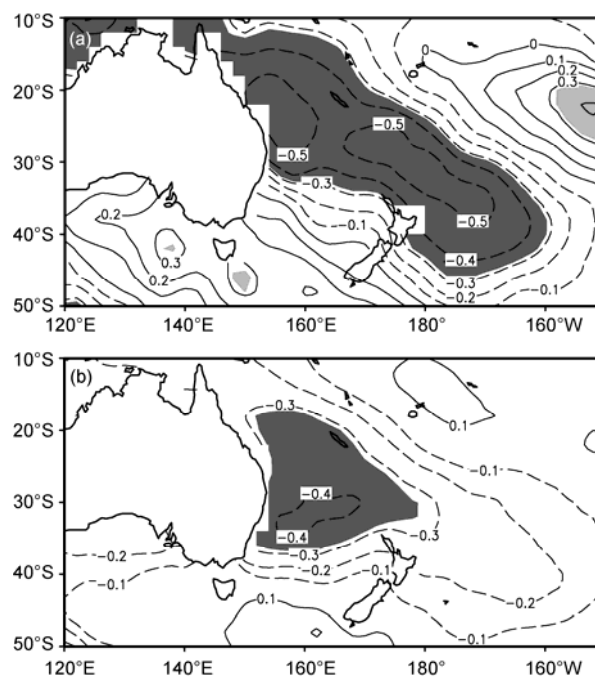


Figure 1 Correlations between JJASO WNPTCF and MAM (a) and JJASO (b) SST. Regions above the 95% significance level are shaded.

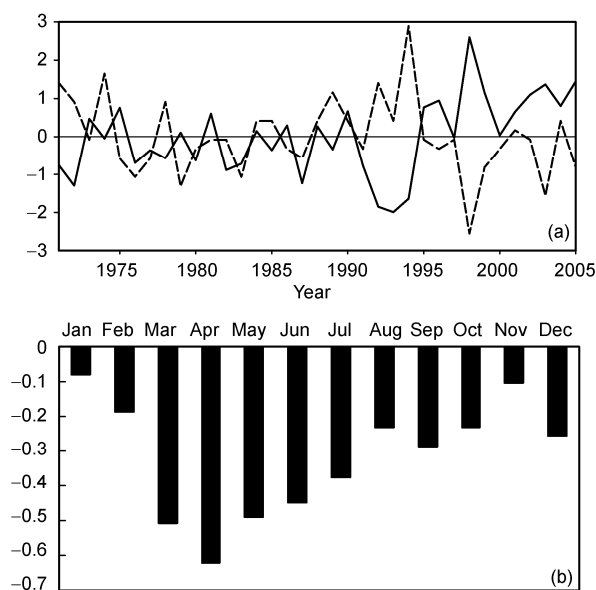


Figure 2 (a) Time series of the normalized MAM EASST (solid line) and JJASO WNPTCF (dashed line). (b) Correlations between JJASO WNPTCF and the monthly SST.

JJASO WNPTCF is negatively correlated to the preceding and simultaneous EASST. Nevertheless, the negative correlations between JJASO WNPTCF and the EASST in March, April and May are the largest, whereas its correlations with the EASST in January and February are not pronounced (not significant at the 95% level).

These results show that the SST anomaly east of Australia in spring can exert significant effects on WNPTCF change. If the SST east of Australia is above (below) normal in spring, the WNPTCF will decrease (increase) in JJASO. To reveal the possible mechanism responsible for their linkage, we analyzed the atmospheric circulations associated with change in spring SST east of Australia using linear regression. Regression coefficients can be obtained by applying the least square method to the equation $y(t) = ax(t) + b$, where $y(t)$ is the physical variable, t is time, $x(t)$ is the time series of the normalized index (EASST or WNPTCF), a is the regression coefficient and b is a constant. The pattern of the regression coefficient a denotes change in variable y (horizontal wind and vertical velocity) corresponding to the x change by one standard deviation. The significance of the regression coefficient was assessed by the Student's t -test [41].

Figure 3(a) and (b) depict regressions of JJASO horizontal winds at 850 and 200 hPa against the spring EASST, respectively. In association with warmer SST east of Australia in spring, an anomalous easterly prevails in the lower troposphere of the tropical western Pacific during JJASO, indicative of a weakened monsoon trough. Concurrently, two anomalous anticyclonic circulations are located on both sides of the equator (Figure 3(a)). In the upper troposphere, the westerly anomaly is predominant over the tropical western Pacific, concomitant with anomalous cyclonic circula-

tions on either side (Figure 3(b)). Such a pattern corresponds to the atmospheric background for fewer TCs, which can be shown by the regressions of the 850 hPa and 200 hPa winds against JJASO WNPTCF. As shown in Figure 3(c) and (d), the atmospheric circulation system related to more (less) WNPTCF comprises the anomalous cyclonic (anticyclonic) circulation over the WNP and anomalous westerly (easterly) over the tropical Pacific in the lower troposphere as well as the anticyclonic (cyclonic) circulation anomaly over the WNP and easterly (westerly) anomaly over the tropical Pacific in the upper troposphere.

Changes in high- and low-level winds may cause atmospheric vertical motion to be abnormal. Figure 4(a) shows that positive values appear in large areas east of 140°E, which indicates that corresponding to anomalous low-level anticyclonic circulation and high-level cyclonic circulation in Figure 3(a) and (b), anomalous subsidence dominates the WNP in JJASO. The regression pattern of the vertical velocity along 0°–30°N upon JJASO WNPTCF displayed in Figure 4(b) is generally the converse of that in Figure 4(a). A large negative anomaly emerges the east of 140°E, implying that anomalous ascending (descending) over the WNP corresponds to more (less) WNPTCF. Therefore, Figure 4 well illustrates that anomalous downward (upward) motion over the WNP in JJASO is related to the warmer (colder) spring SST east of Australia and is unfavorable (favorable) for TC genesis in this region. This further confirms the out-of phase relationship between spring EASST and JJASO WNPTCF.

Changes in high- and low-level winds can also result in variation in the magnitude of the vertical zonal wind shear, which is a crucial environmental condition for TC genesis and development. Studies [1,11,12,24,42,43] have demonstrated the inverse relationship between TC frequency and the vertical zonal wind shear. Low vertical zonal wind shear benefits TC genesis and development. Conversely, high vertical zonal wind shear does not favor TC genesis and development. Such a linkage can be clearly detected in the regression of vertical zonal wind shear against JJASO WNPTCF (Figure 5(b)), which shows negative coefficients in the major TC genesis region. Figure 5(a) shows regressions of the JJASO vertical zonal wind shear against the spring EASST. The pattern of positive anomalies in the major TC genesis region over the WNP is almost opposite to that in Figure 5(b). Therefore, vertical zonal wind shear is intensified during JJASO in association with the positive phase of spring SST east of Australia, disadvantageous for TC genesis over the WNP, and vice versa.

To sum up, when spring SST east of Australia is warmer (colder) than normal, anomalous low-level anticyclonic (cyclonic) and high-level cyclonic (anticyclonic) circulations occur over the WNP during the following JJASO. Correspondingly, the airflow descends (ascends) and the vertical zonal wind shear strengthens (weakens). These conditions are unfavorable (favorable) for TC genesis and

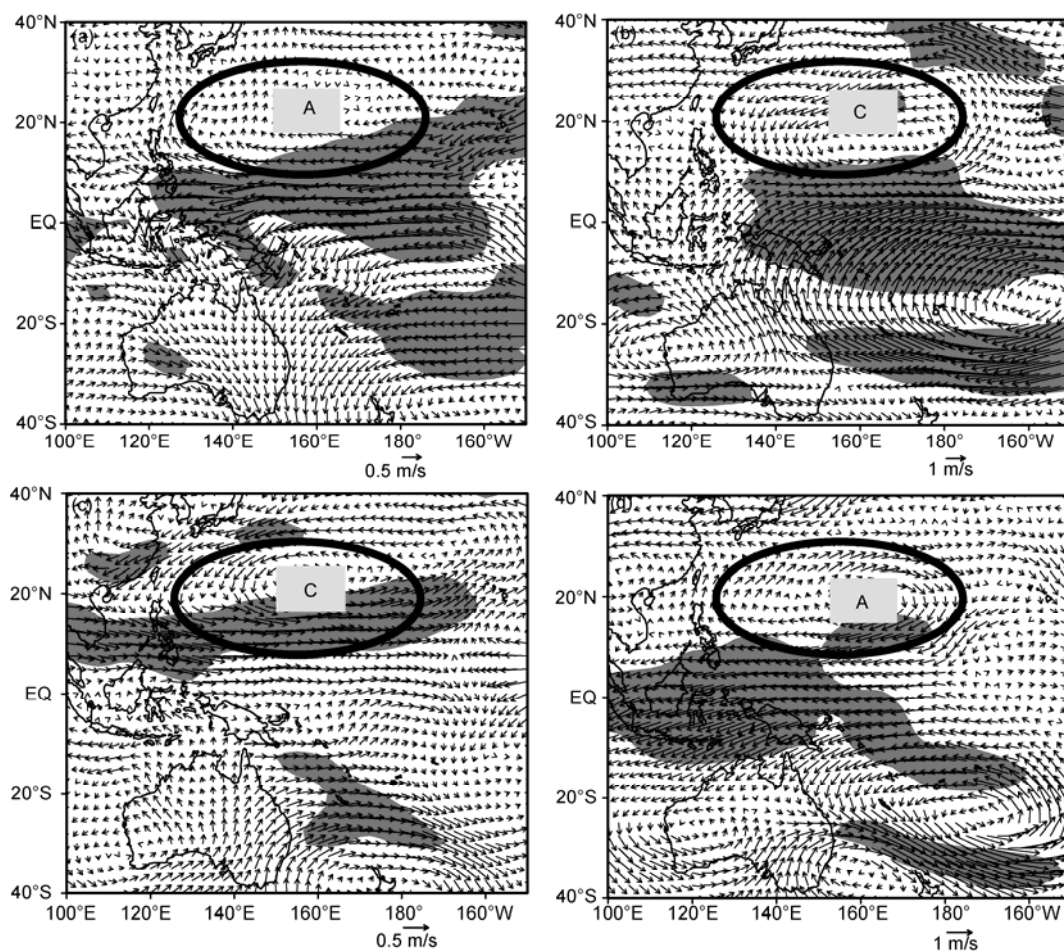


Figure 3 Regressions of JJASO winds at 850 hPa (UV_{850}) and 200 hPa (UV_{200}) respectively against MAM EASST and JJASO WNPTCF. (a) UV_{850} -EASST; (b) UV_{200} -EASST; (c) UV_{850} -WNPTCF; (d) UV_{200} -WNPTCF. Regions above the 95% significance level are shaded. A and C in the figures denote anticyclonic circulation and cyclonic circulation, respectively.

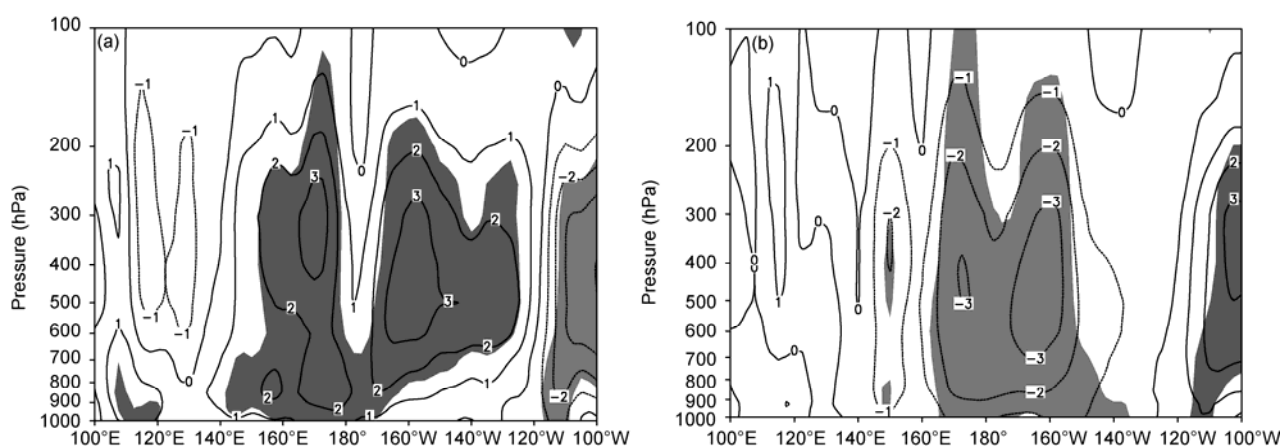


Figure 4 Cross-section of regressions of JJASO vertical velocity (in $10^{-3} \text{ Pa s}^{-1}$) along 0° - 30°N against MAM EASST (a) and JJASO WNPTCF (b). Regions above the 95% significance level are shaded.

hence the WNPTCF decreases (increases).

How does the spring SST east of Australia affect atmospheric circulation over the WNP? As is known, atmospheric circulation change over the tropical Pacific has a good seasonal persistence [28,44]. This strong seasonal persistence

may play an important role in their linkage. To further test our speculation, the regression of 200 hPa winds against the EASST in spring is plotted in Figure 6. Anomalous anticyclonic circulation, cyclonic circulation and cyclonic circulation can be observed from south to north in the Pacific. The

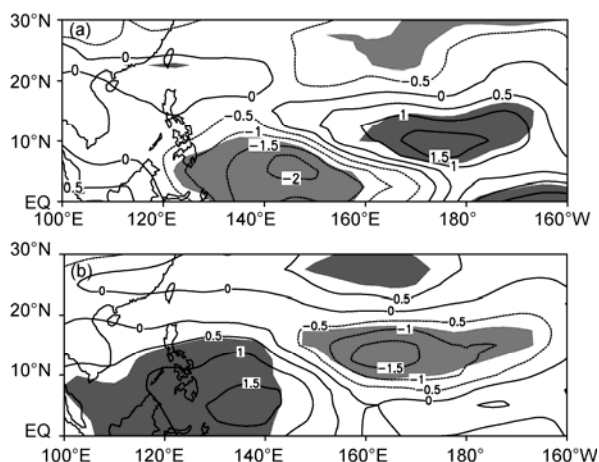


Figure 5 Regressions of JJASO vertical zonal wind shear (unit: m/s) against MAM EASST (a) and JJASO WNPTCF (b). Regions above the 95% significance level are shaded.

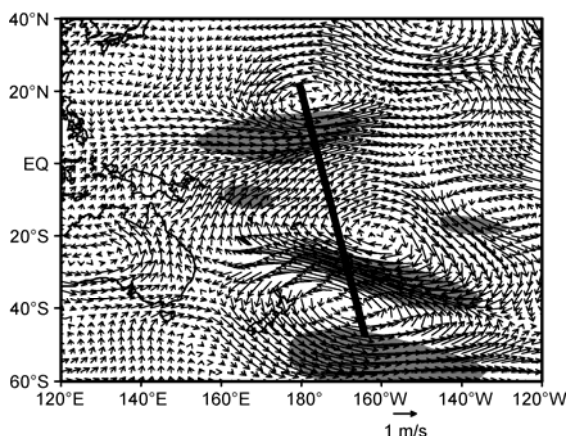


Figure 6 Regressions of the horizontal wind (unit: m/s) at 200 hPa against EASST in spring. Regions above the 95% significance level are shaded.

tropical Pacific is occupied by an anomalous westerly. Therefore, SST east of Australia can induce the tropical atmospheric circulation anomaly in spring via the meridional teleconnection. Due to the seasonal persistence of the tropical atmospheric circulation, such an anomaly may last from MAM to JJASO and subsequently affect TC activity over the WNP. Seen in Figure 7, the upper-tropospheric zonal wind anomaly over the tropical Pacific, which results from change in spring SST east of Australia, can persist from spring until October.

3 Conclusions

We addressed the influence of spring SST east of Australia on WNPTCF change in JJASO. The JJASO WNPTCF is correlated negatively to spring SST east of Australia. The correlation coefficients between MAM EASST and JJASO WNPTCF were -0.57 and -0.55 respectively for the non-detrended and detrended time series in the period 1971–

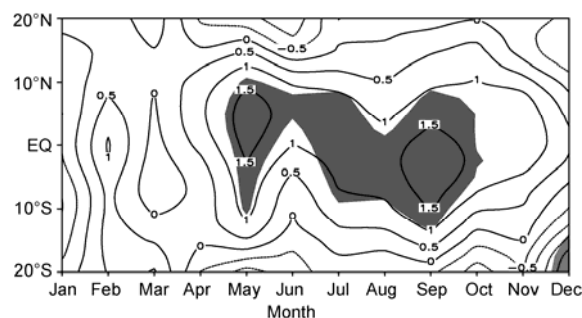


Figure 7 Regressions of monthly zonal wind (unit: m/s) at 200 hPa against MAM EASST. Regions above the 95% significance level are shaded.

2005, and both were significant at the 99.9% level. It is thus suggested that spring SST east of Australia may be a potential indicator affecting WNPTCF. If the SST east of Australia is in the positive (negative) phase in spring, fewer (more) TCs will occur over the WNP in the following JJASO.

We identified a possible mechanism responsible for the effect of spring SST east of Australia on JJASO WNPTCF. A positive phase of spring SST east of Australia is followed by a cyclonic circulation anomaly in the upper troposphere, and an anticyclonic circulation anomaly in the lower troposphere over the WNP in JJASO. Consequently, the airflow subsides to constrain convective activity. Meanwhile, the vertical zonal wind shear increases in the major TC genesis region. These conditions do not favor TC genesis and development, and thus the WNPTCF is decreased. The opposite situation favoring TC genesis over the WNP corresponds to the negative phase of spring SST east of Australia. Further analysis indicates that spring SST east of Australia can simultaneously change the tropical circulation via atmospheric teleconnection. Due to the strong seasonal persistence of the tropical circulation, the tropical circulation anomaly can persist from spring to JJASO, and then potentially modulate the atmospheric circulations associated with WNPTCF.

This candidate mechanism is a preliminary explanation. Other processes may also act in their linkage. Because air-sea interactions are complex, more in-depth analyses are needed to clarify the detailed physical processes and dynamic mechanisms of the influence of spring SST east of Australia on the WNPTCF. Our statistical conclusions also need to be validated by numerical models. So, our future research will attempt to conduct rational sensitivity experiments with state-of-the-art climate models.

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